Impact of Typhoons on the Western Pacific Ocean (ITOP) DRI: Numerical Modeling of Ocean Mixed Layer Turbulence and Entrainment at High Winds

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LONG-TERM GOALS

A significant source of uncertainty in parameterizations of ocean boundary layer dynamics lies in our inability to accurately represent the role of surface waves in upper-ocean Langmuir turbulence, and in the resulting mixed layer entrainment processes. This study contributes to our understanding of the role of waves and Langmuir turbulence in the context of high wind forcing by typhoons and hurricanes, and also contributes to our ability to consistently parameterize these processes across a much wider wide range of wind speed and sea state forcing conditions.

OBJECTIVES

This collaborative DRI is focused on measuring and modeling the response of the upper ocean to strong typhoons both in simple, open ocean conditions and in the more complex conditions caused by ocean eddies and preconditioning by prior storms. The measurement and modeling activities include a focus on the impact of surface waves, air-sea fluxes and the temperature, salinity and velocity structure of the upper ocean. The goals of this effort are to understand key upper ocean processes, test upper ocean models, develop and test new parameterizations of upper ocean physics used and study the feedback from the ocean to typhoon intensity.

APPROACH

The approach of the the modeling component is to use field observations to force Large Eddy Simulation (LES) and upper ocean turbulence models in equivalent numerical cases and to use model-data comparison to test the theoretical basis of mixed layer turbulence scalings and parameterizations. The strategy is to test our physical theories and parameterizations of mixed layer dynamics against data by incorporating them realistically in turbulence-resolving LES models with embedded virtual measurements. Verification of the underlying theories can then be achieved through direct model-data comparison, using observations of ocean waves and turbulence under a wide range of oceanic conditions, and leading to improved parameterizations of upper ocean turbulence. The strong and isolated wind forcing in tropical cyclones provides an ideal environment for testing theories and parameterizations of the role of surface waves in the ocean mixed layer. This follows similar work in

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2013**	2. REPORT TYPE	3. DATES COVERED **00-00-2013 to 00-00-2013**

4. TITLE AND SUBTITLE **Impact of Typhoons on the Western Pacific Ocean (ITOP) DRI: Numerical Modeling of Ocean Mixed Layer Turbulence and Entrainment at High Winds**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Washington,Applied Physics Laboratory,1013 NE 40th St,Seattle,WA,98105**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**6**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

CBLAST exploiting the comprehensive view of boundary layer turbulence made possible by the combination of Lagrangian float and EM-APEX measurements. Throughout the ITOP DRI, work has focussed on developing and testing an improved second moment closure (SMC) to represent the impact of Langmuir turbulence.

WORK COMPLETED

Encouraged by good quantitative comparisons between LES models and Lagrangian float observations at medium to high winds in *Harcourt & D'Asaro* (2008), henceforth HD08, and subsequent refinements in the interpretation of observations in *Harcourt & D'Asaro* (2010), a SMC incorporating the Craik-Leibovich (CL) vortex force has been developed to predict upper ocean turbulence, including under the winds of tropical cyclones. This *Harcourt* (2013) model, henceforth H13, more correctly represents the effect of these vortex force terms due to the interaction of surface wave Stokes drift and Eulerian current shear within the mixed layer. The H13 model is tuned to reproduce not only the HD08 scaling of vertical kinetic energy (VKE) based on steady-state forcing at medium to very high winds, but also the time-dependent LES simulations of rapid deepening below the maximum winds in tropical cyclones. The HD08 VKE scaling continues to be consistent with Lagrangian float observations in typhoons Megi and Fanapi obtained during ITOP, though some details in these and other recent hurricanes are subject to uncertainties in local wind forcing. Further development of the H13 model under ITOP has focused on transferring the treatment of Craik Leibovich vortex force terms into the GOTM modeling framework (*Burchard and Bolding*, 2000), which encompasses several other versions of second moment closures, and on developing appropriate 'realizability conditions' to improve model skill and stability.

RESULTS

The new H13 closure model incorporates significant Langmuir turbulence modifications into the popular $q^2l - q^2$ Mellor-Yamada 2.5 SMC. These changes are derived by properly accounting for the Craik-Leibovich vortex force terms in the algebraic Reynolds stress model (ARSM). Prior modifications of turbulence closure models for Langmuir turbulence accounted only for increased CL vortex force production of turbulent kinetic energy and length scales in the prognostic q^2 and q^2l equations (*Kantha and Clayson*, 2004) that are used to determine vertical eddy diffusivity $K_H = S_H\, q\, l$ and viscosity $K_M = S_M\, q\, l$. The inclusion of CL vortex force terms in the ARSM additionally requires new flux closures:

$$\overline{u'w'} = -K_M \partial_z u - K_M^S \partial_z u, \qquad \overline{v'w'} = -K_M \partial_z v - K_M^S \partial_z v, \qquad \overline{w'\theta'} = -K_H \partial_z \theta,$$

where: 1) A component of the momentum flux is directed down the gradient $\partial_z \mathbf{u}^S$ of the Stokes drift, as foreshadowed by prior LES studies (*McWilliams and Sullivan 2000*; *Smyth et al.,* 2002*;* and *McWilliams et al.* 2012); 2) new expressions for the 'stability functions' S_H, S_M, S^S_M, obtained by solution of the ARSM linear equations, now depend on nondimensional forcing functions $G_V = l^2 q^{-2}(\partial_z \mathbf{u} \cdot \partial_z \mathbf{u}^S)$ and $G_S = l^2 q^{-2} |\partial_z \mathbf{u}^S|^2$ arising from Stokes shear $\partial_z \mathbf{u}^S$, in addition to the traditional SMC dependence on $G_H = l^2 q^{-2} N^2$ and $G_M = l^2 q^{-2} |\partial_z \mathbf{u}|^2$ representing the effects of stability N^2 and Eulerian shear $\partial_z \mathbf{u}$. Increased stability function values are the largest contributor to large, near-surface increases in vertical eddy coefficients due to Langmuir turbulence.

Figure 1 demonstrates this effect of the CL vortex force in both the extreme high winds and young seas of tropical cyclones, and, for comparison, in more typical conditions of open ocean wind-forced seas with more fully developed seas. The large changes in both the magnitude and relative scale of the eddy viscosity K_M and diffusivity K_H are due primarily to changes in the stability functions with the inclusion of CL forcing in the ARSM. These modifications are sensitive to the relative depth scale of the CL forcing, as identified in the HD08 scaling. The resulting changes to the second moment closure (SMC) go well beyond the additional production of turbulent kinetic energy and length scale because they account for the very different mixing impacts of production into the different components of TKE in the ARSM.

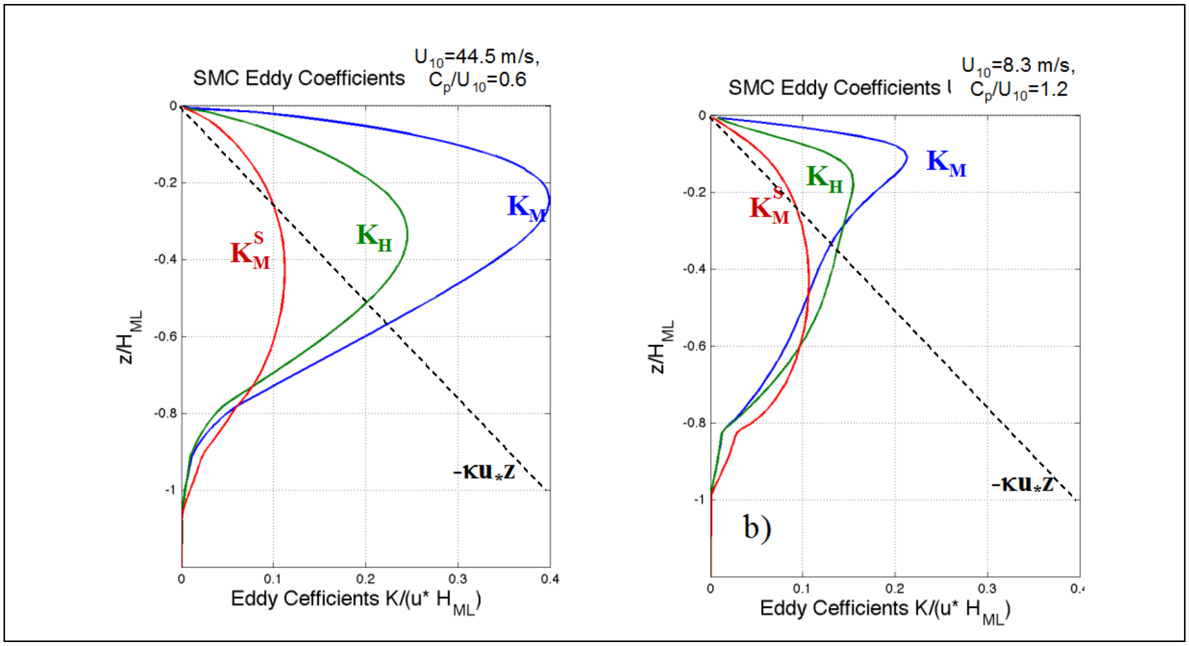

Fig. 1. Impact of CL vortex force on SMC model eddy coefficients K_H, K_M, K^S_M in (left) very strong Langmuir forcing at 45.5 m/s winds in young seas and (right) weaker Langmuir forcing at 8 m/s in mature seas. Elevation above $K \sim \kappa u^*|z|$ wall boundary layer scaling is due to CL vortex force effects from surface waves on the stability functions. This is sensitive to the relative scale of the mixed layer depth and the Stokes e-folding scale (~ peak wavelength), which is relatively larger even in the young seas at high winds (left) than it is in the mature seas at moderate winds (right).

The new turbulence model improves model-data comparisons of upper ocean shear (Fig 2) below typhoons and hurricanes, but it is not without some still outstanding defects in comparisons with Lagrangian float-observed vertical kinetic energy. Significant further efforts have been put into recasting its salient impacts into the framework general ocean turbulence model (GOTM; *Burchard and Bolding*, 2000). Adapting the changes driven by properly including the CL vortex force in the Reynolds Stress closure into the GOTM framework was motivated by both larger class of expressions implemented for pressure-strain closure and by the different approach to modeling the turbulence length scale under the generic length-scale equation of *Umlauf and Burchard* (2003).

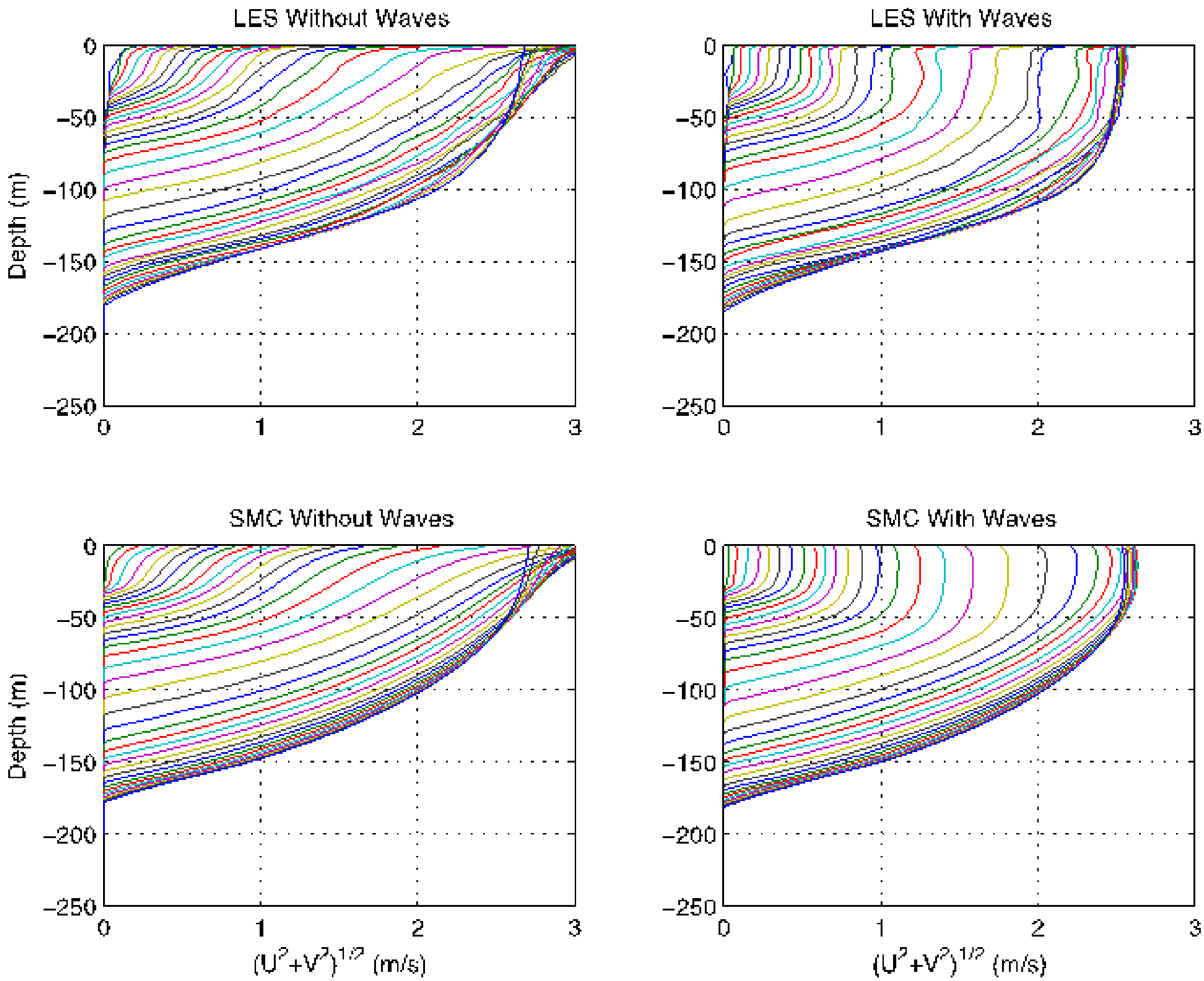

Fig. 2. Simulations of upper ocean shear below the passage of a tropical cyclone, compared between the new second moment closure (SMC) and turbulence-resolving LES, both with and without including the Craik-Leibovich effect due to the Stokes drift of surface waves.

Following this plan, a generalized closure including the correct CL vortex production terms was composed as a relatively large linear algebra problem and solved using a symbolic math program. While the resulting expression is a complex function of closure constants, the solution gives the stability functions (for determining eddy coefficients) as ratios of polynomials in the local nondimensional forcing scales of stability, Eulerian shear, Stokes shear, and the product of Stokes and Eulerian shear, and the expressions are straightforward to compute. This was a significant achievement, but analyzing the new algebraic solution (relating vertical eddy coefficients to energy and dissipation or its length scale) showed the improved model based on the GOTM framework to be not significantly better than the earlier one (*Harcourt*, 2013), unless a non-standard dependence on nondimensional forcing was introduced into the model 'constants'. While the GOTM framework contains many more closure expressions for the problematic pressure-strain correlations of Langmuir turbulence, none of these on their own have quite the form needed to improve the model even as the coefficients are fit to LES solutions of upper ocean turbulence ranging between moderate to very high winds and with variable sea states.

Comparison between model behavior and the most remarkable wave-related features of typhoons and hurricanes has run between been very good and mixed. While there is generally an agreement between vertical kinetic energy measured by floats and the second moment closure predictions in their mixed layer averages, their profiles differ significantly due to the inadequate closure of the pressure-strain correlation terms mentioned above. More troubling, Lagrangian float measurements immediately behind the eye of tropical cyclones show a drop in vertical kinetic energy for an extended period not yet directly reproduced in duration by the closure or by the LES in simulations based on measured winds and the Stokes drift from modeled wave spectra. There is considerable uncertainty in surface forcing and it may well be that the modeled wave spectra and winds in this rear quadrant are not accurate as there is a well-grounded expectation that vertical mixing driven by the CL vortex force will be significantly inhibited when the wind and waves are perpendicular, but in the meantime presenting a clear verification of this phenomenon using direct model-data comparisons has not yet been achieved. Outstanding problems may well be related to the difference between momentum flux from the atmosphere to the waves, and between waves and the ocean (Eulerian) current. Implementing the new H13 SMC of Langmuir turbulence in a coupled model containing at least an explicit wave action model and a regional-scale ocean model would present the best opportunity to solve such problems.

IMPACT/APPLICATIONS

Surface waves are believed to play a key role in the upper ocean boundary layer, yet do not appear explicitly in any of the major boundary layer parameterizations used in ocean circulation or climate models. Addressing this defect will lead to mixed layer models with turbulence intensity and entrainment efficiency, scaled by wind stress, that increase with surface wave age, in the presence of swell. While subsurface shear may dominate pycnocline mixing under inertially resonant wind forcing conditions, variability in mixed layer energy due to surface waves will play a significant role in deepening the layer when this is not the case. A boundary layer model that includes sea state dependencies, in addition to the usual dependencies on surface stress, buoyancy flux, and subsurface shear, will ultimately be more accurate than one that does not. Predicting the effects of Langmuir turbulence in the upper ocean is of widespread interest well beyond the air-sea-waves coupling and the ocean mixing impacts of typhoons and hurricanes. These include large contributions to air-sea gas exchange, climate and productivity effects, ocean microlayer dynamics, the production of aerosols, the effects of bubble distributions on optical scattering and sound propagation, the dispersion of insoluble pollutants such as plastic particulates and oil, ship track studies, and the systematic biases of buoyant instrument platforms.

RELATED PROJECTS

Typhoons DRI continues previous work in the Hurricane component of CBLAST DRI. Development of SMC closure pursued in conjunction with an NSF/ARRA project ‘Wave Impacts’ that is focused for contrast on a comparison case of a lake boundary layer without significant wave forcing.

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